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HEAVY ION INVESTIGATIONS

Richard D. Sharp, et al

Lockheed Missiles and Space Company, Incorporated

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HEAVY ION INVESTIGATIONS

FINAL REPORT

CONTRACT N00014-73-C-0165

30 July 1973

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APPENDIX B

OBSERVATIONS OF ENERGETIC HEAVY IONS NEAR SOLAR MAXIMUM

R. D. Sharp, R. G. Johnson, and E. G. Shelley
Lockheed Palo Alto Research Laboratory
Lockheed Missiles & Space Company, Inc.
Palo Alto, California 94304

ABSTRACT

Heavy ions with energies between 1 and 9 keV have frequently been detected with an energetic ion mass spectrometer on the satellite 1969-25B during the period March 1969 to August 1970. Their identification as O^+ ions of ionospheric origin has been inferred from a comparison with the more complete mass measurements with an improved spectrometer on the satellite 1971-089A, and from considerations of ionospheric and solar wind abundance ratios. Data from nine magnetic storms have been analyzed, and the peak responses occurred at L values between 3.4 and 6.4, and at magnetic local times between 21.8 and 4.5 hours. A maximum flux of approximately 0.1 erg/cm^2-sec-sterad was observed during the 23-24 March 1969 storm.

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13. ABSTRACT

This was a research program to investigate the properties of the newly discovered fluxes of energetic O^+ ions which have been found to populate the magnetosphere during magnetic storms. Measurements on these ions were obtained with the ARPA experiment on the OV1-18 satellite, and the data from that experiment were analyzed under this contract. During this program we surveyed a representative fraction of the data extending over the entire 18-month lifetime of the satellite and identified examples of O^+ fluxes during a number of magnetic storms. The locations of the peak intensities of the heavy ions on selected passes were investigated as a function of invariant latitude, magnetic local time and pitch angle. Their occurrence was found to maximize at an invariant latitude of about 63° and they were spread relatively uniformly over magnetic local times from 19 to 06 hours. The pitch angles at which the peak fluxes were observed were distributed relatively uniformly over the upper hemisphere. The latitudinal distribution of the O^+ ions with respect to the plasmapause was determined on seven occasions by comparing the satellite data with ground-based measurements of stable auroral red arcs. The low-latitude limit of the O^+ ions was found to be about one L unit poleward of the plasmapause. The spatial relationship between the O^+ ions and simultaneous satellite measurements of the ambient cold plasma and energetic particle fluxes were investigated in detail on an orbit during the 24 March 1969 magnetic storm. The most intense O^+ fluxes were found to be located equatorward of the trapping boundary for energetic electrons and on a steep density gradient in the cold plasma.

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HEAVY ION INVESTIGATIONS
FINAL REPORT
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Report Summary

This was a research program to investigate the properties of the newly discovered fluxes of energetic O^+ ions which have been found to populate the magnetosphere during magnetic storms. Measurements on these ions were obtained with the ARPA experiment on the OV1-18 satellite, and data from that experiment were analyzed under this contract.

During this program we surveyed a representative fraction of the data extending over the entire 18-month lifetime of the satellite and identified examples of O^+ fluxes during a number of magnetic storms.

The locations of the peak intensities of the heavy ions on selected passes were investigated as a function of invariant latitude, magnetic local time and pitch angle. Their occurrence was found to maximize at an invariant latitude of about 63° and they were spread relatively uniformly over magnetic local times from 19 to 06 hours. The pitch angles at which the peak fluxes were observed were distributed relatively uniformly over the upper hemisphere.

The latitudinal distribution of the O^+ ions with respect to the plasmapause was determined on seven occasions by comparing the satellite data with ground-based measurements of stable auroral red arcs. The low latitude limit of the O^+ ions was found to be about one L unit poleward of the plasmapause. The spatial relationship between the O^+ ions and simultaneous satellite measurements of the ambient cold plasma and energetic particle fluxes were investigated in detail on an orbit during the 24 March 1969

magnetic storm. The most intense O^+ fluxes were found to be located equatorward of the trapping boundary for energetic electrons and on a steep density gradient in the cold plasma.

This initial survey of the data from the ARPA energetic ion experiment on OV1-18 has revealed that there is much new and significant information on the interaction between the magnetosphere and the ionosphere contained within the data. The O^+ ions are most likely accelerated by some ionospheric process which is related to other ionospheric disturbance phenomena important to communications and weapons effects studies. The presence of energetic He^+ ions which may also have been accelerated from the cold ionospheric plasma was recently detected in this body of data. No previous measurements of energetic He^+ have been reported in the literature. We recommend that further analyses on the morphology of the O^+ and He^+ fluxes be performed using the OV1-18 data since it is the only existing data near the solar cycle maximum. Also, it is now evident that the energetic oxygen ions occur frequently on a worldwide scale and are at least as dynamic as the ring current protons. Thus, a sizeable data base will be required to thoroughly understand this important geophysical phenomena which is not accounted for by any of the existing theoretical models of the ionosphere and magnetosphere. We will submit a follow-on proposal for further work on the OV1-18 data which were acquired under an ARPA-funded ionospheric program.

Statistical Results at Positions of Peak Intensities

Satellite data from 11 magnetic storms were analyzed and the position of the peak O^+ flux intensity on 16 selected satellites passes was identified. The L value, magnetic local time (auroral time) and pitch angle at these times were calculated. Table I summarizes some of the data from these events. Figure 1 shows the distribution in L,AT space indicating a broad maximum near L = 5 and a rather uniform distribution in auroral time over the nighttime sector. Figure 2 shows the distribution of the pitch angles at which the peak fluxes were observed. It is seen that they are distributed relatively uniformly over the upper hemisphere consistent with an isotropic pitch angle distribution except for the loss cone. The geophysical significance of this

<u>Table I</u>. OV1-18 O^{+} Events - Peak Flux Positions

Date	Acq.	Storm	UT (Secs)	L	Auroral Time (Hours)
March 24, 1969	97	16	585	3.4	1.2
	104	16	65332	7.6	19.7
April 13, 1969	403	22	43688	5.2	23.6
April 28, 1969	634	26	48462	4.8	23.3
May 13, 1969	858	28	64292	5.7	21.8
May 15, 1969	888	29	49194	4.3	23.8
	892	29	83439	4.4	2.4
September 29, 1969	2970	44	67676	4.4	2.6
December 5, 1969	4020	56	70673	5.0	0.4
January 30, 1970	4862	4	75433	6.5	4.5
February 17, 1970	5114	--	77557	5.4	0.8
March 27, 1970	5687	12	38855	5.8	4.1
April 21, 1970	6069	18	35237	4.9	4.9
April 22, 1970	6084	18	33689	6.4	5.3
	6084	18	30157	5.4	3.0
June 27, 1970	7122	26	35826	3.8	4.1

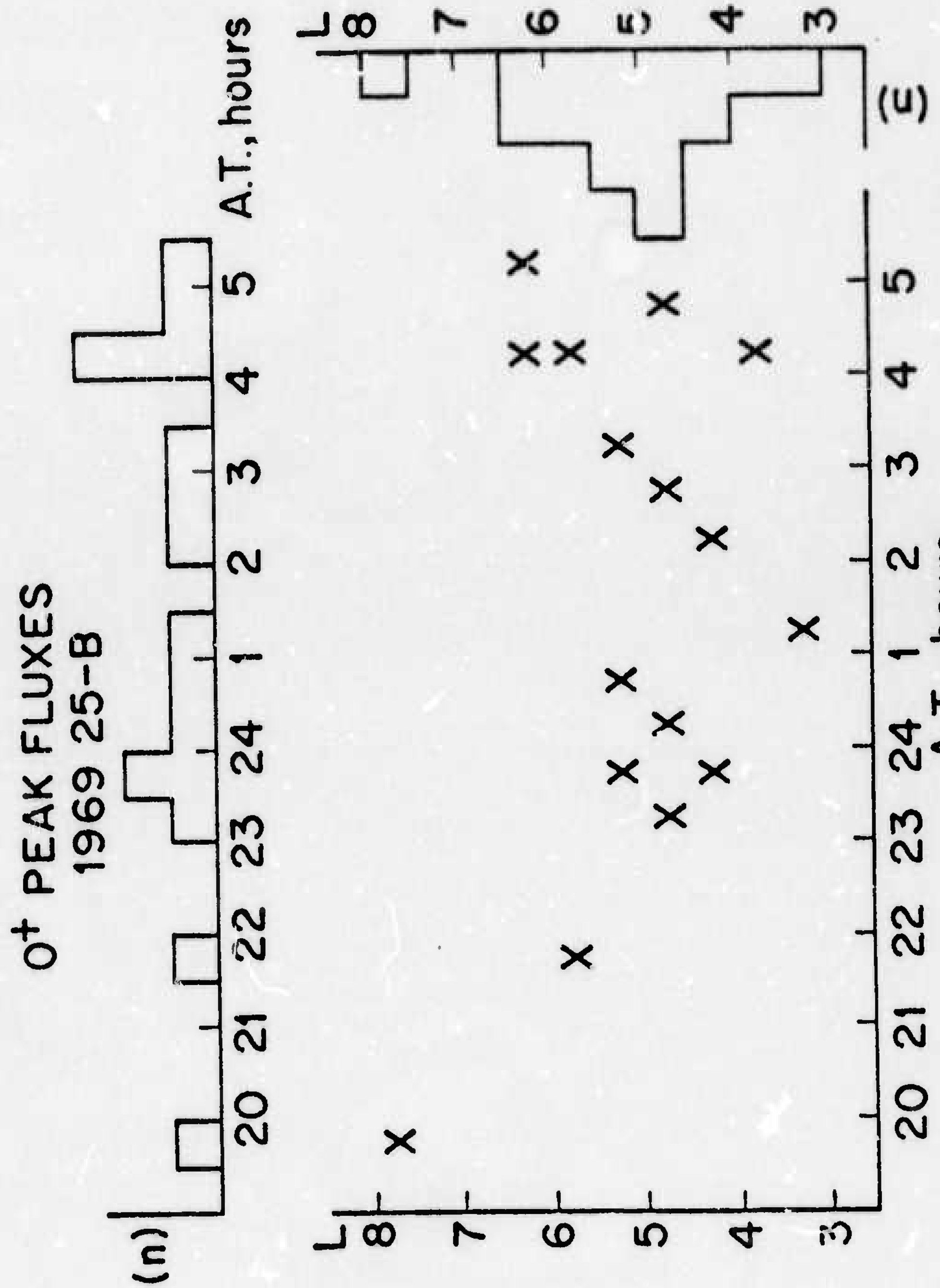

FIGURE 1

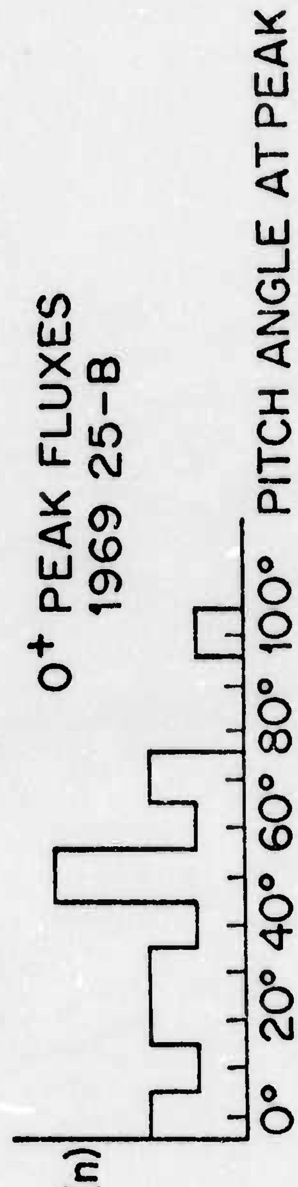

FIGURE 2

evidence for the isotropy of the angular distributions of the O^+ ions is discussed in more detail in Appendix A. The statistical results described above were reported at the spring meeting of the American Geophysical Union (Sharp et al., 1973†). The abstract of this talk is included as Appendix B.

Latitudinal Variations

The spatial relationships between the O^+ ions and various other geophysical phenomena were investigated in some detail on one orbit during the 24 March 1969 magnetic storm. Comparisons with the positions of stable auroral red arcs were obtained on seven occasions during three magnetic storms. These results are described in a paper prepared for submission to the Journal of Geophysical Research entitled "Energetic O^+ Ions in the Magnetosphere" by R. D. Sharp, R. G. Johnson, E. G. Shelley and K. K. Harris which is included as Appendix A.

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† Sharp, R. D., R. G. Johnson, and E. G. Shelley, "Observations of Energetic Heavy Ions Near Solar Maximum," Trans. Am. Geophys. U., 54, 432, 1973.

APPENDIX A

ENERGETIC O^+ IONS IN THE MAGNETOSPHERE

R. D. Sharp, R. G. Johnson, E. G. Shelley and K. K. Harris

June 1973

Lockheed Palo Alto Research Laboratory
Lockheed Missiles & Space Company, Inc.
Palo Alto, California 94304

ENERGETIC O^+ IONS IN THE MAGNETOSPHERE

R. D. Sharp, R. G. Johnson, E. G. Shelley and K. K. Harris
LOCKHEED PALO ALTO RESEARCH LABORATORY
Palo Alto, California 94304

ABSTRACT

Observations of energetic O^+ ions are reported on seven occasions during three magnetic storms in 1969. The data were acquired from an energetic ion mass spectrometer experiment on the satellite 1969-25B. Measurements were made at 1, 3, and 9 keV. Data from an orbit on March 24, 1969 are examined in some detail. The O^+ fluxes are shown to exhibit a similar morphology to that reported by Shelley et al. [1972] for the December 17, 1971 storm. The latitude distribution of the O^+ fluxes is compared to simultaneous satellite and ground-based measurements of other phenomena. The most intense O^+ fluxes were found to be located equatorward of the high-latitude boundary of locally mirroring energetic electrons, and poleward of a stable auroral red arc. They were located on a steep density gradient in the ambient cold plasma at the satellite altitude of 480 km. A comparison of the location of the O^+ fluxes on six other occasions with SAR-arc observations acquired during the same storms indicates that the low-latitude limit of the O^+ is on the average about one L unit poleward of the arc.

INTRODUCTION

Shelley et al. [1972] reported the discovery of intense fluxes of O^+ ions with energies of up to 12 keV during the December 17, 1971 magnetic storm. The O^+ ions were observed over a wide range of latitudes ($2.4 \lesssim L \lesssim 9$) at altitudes near 800 km. The measurements were made with a set of three energetic ion mass spectrometers on the satellite 1971-089A. The spectrometers each consisted of a Wien-type velocity filter in series with an electrostatic analyzer followed by a channel-electron-multiplier (see Figure 1) providing both energy-per-unit-charge and mass-per-unit-charge information on the measured particles. Identification of the observed heavy ions was accomplished at nine separate energies providing unambiguous proof of the existence of energetic ions with mass per unit charge = 16 ± 2, with the uncertainty determined by the mass dispersion of the spectrometers. Their further identification as O^+ ions of ionospheric origin was inferred from the high abundance of this species in the thermal plasma of the ionosphere over a wide altitude range [Taylor, 1973] and the lack of other credible hypothesis. The upper left panel of Figure 2 taken from Shelley et al. [1972] shows a composite mass-per-unit-charge spectrum from the 1971-089A data containing observations of 1-keV protons and O^+ ions averaged over different periods on revolution 876 (Dec. 17, 1971).

An early version of the energetic ion mass spectrometer was flown on the satellite 1969-25B (OV1-18) which was launched on March 18, 1969 into a 99° inclination orbit with apogee at 590 km and perigee at 470 km. The 1969-25B instrument also consisted of three separate spectrometers (referred to in the following as CXA-1, -2, and -3), but they were operated at fixed

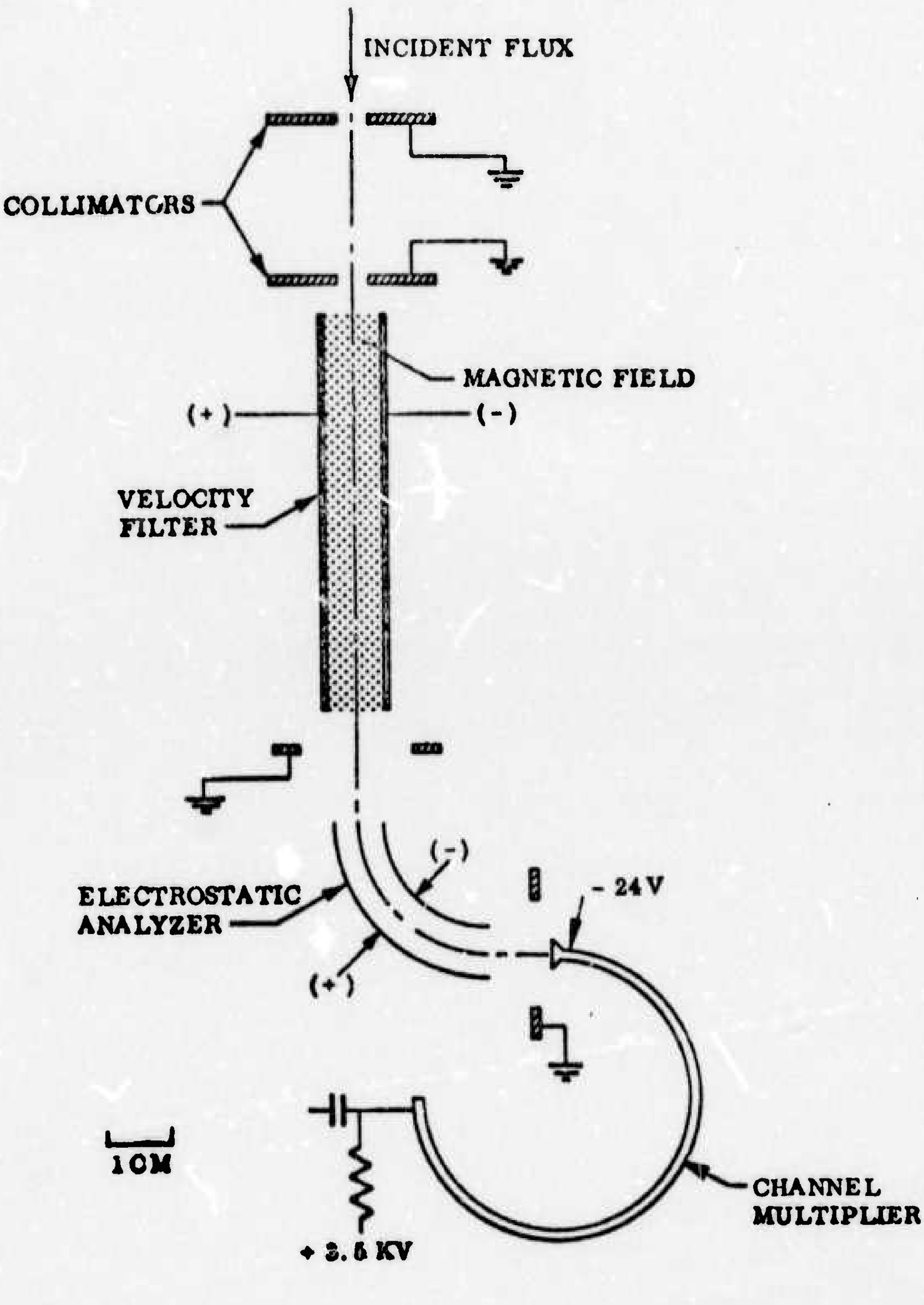
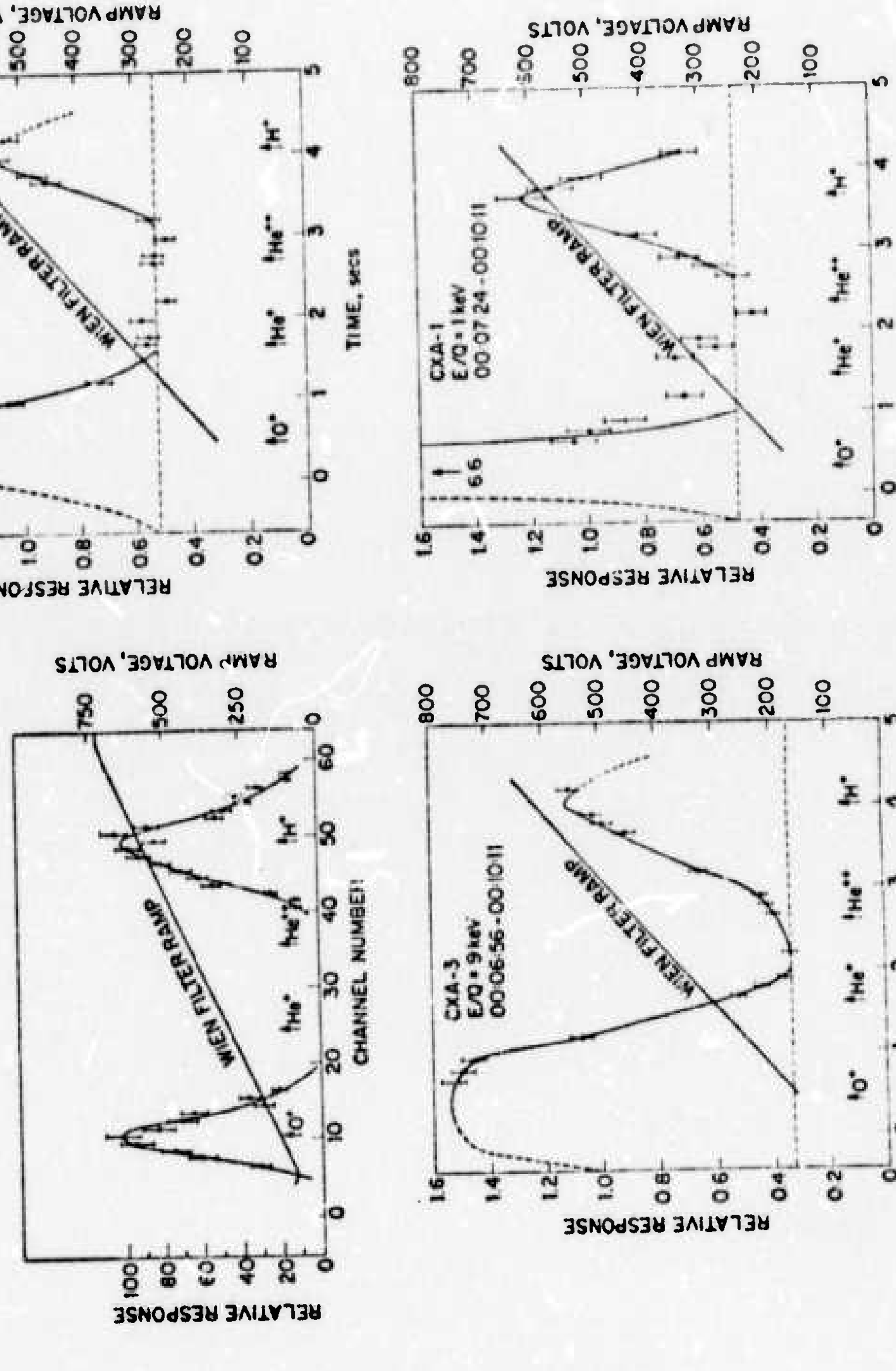

INCIDENT FLUX
COLLIMATORS
MAGNETIC FIELD
(+)
(-)
VELOCITY FILTER
ELECTROSTATIC ANALYZER
(-)
(+)
- 24 V
10M
+ 3.5 KV
CHANNEL MULTIPLIER

FIGURE 1

energies per unit charge of 1, 3 and 9 keV, providing more limited spectral information than the 1971-089A instrument. The velocity filters each consisted of a 1.5-kilogauss magnetic field crossed with an electric field which varied over a linear ramp of 3.86 seconds duration, during which the ratemeter on each channel was sampled 16 times. The ratemeter time constants were approximately 0.2 seconds. One of these spectrometers is illustrated in Figure 1. The mass resolution of this instrument was not as good as the 1971-089A spectrometer and because of bandwidth limitations, there were fewer points available on the mass-per-unit-charge sweep. Also, the sweep did not extend over as wide a range. This is illustrated in the other three panels of Figure 2 which show mass-per-unit-charge spectrums at the three energies per unit charge sampled by the 1969-25B spectrometer. The data were acquired during the March 24, 1969 magnetic storm. The spectrums all show protons and a rise at the high mass-per-unit charge end of the Wien filter voltage ramp which we now identify as being due to O^+ ions on the basis of the more definitive data from 1971-089A. The O^+ ions were observed on many occasions over the eighteen-month lifetime of the 1969-25B satellite, generally during magnetic storms, which occurred quite frequently during this active period near solar maximum. Because the mass-per-unit-charge sweeps of the three channels of the 1969-25B instrument did not extend to low enough values to go over the peak of the mass 16 response functions, their mass could not be uniquely determined from that data alone. Their identification is made now on the basis of their morphological similarity to the storm time O^+ fluxes observed in the more recent experiment. These similarities will be described below. The 1969-25B data are a valuable supplement to the 1971-089A results despite



CXA-2
E/Q = 3 keV
CXA-1
E/Q = 1 keV
CXA-3
E/Q = 9 keV
WIEN FILTER RAMP
RELATIVE RESPONSE
RAMP VOLTAGE, VOLTS
TIME, secs
CHANNEL NUMBER

FIGURE 2

the limitations of the early instrument since they provide confirmation of the existence of the ions with an experiment on a different satellite, in a different altitude range. They are also of value because of the availability of different kinds of correlative data on the earlier satellite and of published results from ground-based observatories during the many storms of the more active 1969 period near solar maximum. This report will focus on the spatial relationships of the O^+ ions to other energetic particles, to thermal plasma density gradients measured on the same spacecraft, and to the plasmapause as determined by ground-based observations of stable auroral red arcs (SAR-arcs).

MARCH 24, 1969 STORM

As indicated above, Figure 2 shows the mass-per-unit-charge spectrums from the three 1969-25B spectrometers obtained on a passage over the northern hemisphere near local midnight on March 23/24, 1969 during a magnetic storm. The dotted response functions illustrated for the O^+ peaks beyond the range of measurements were inferred from the known H^+ response functions for these spectrometers and from flight data from the 1971-089A instrument where the ramp extended over the entire O^+ peak. The times over which the data are summed are indicated in the figures. One sees that on this occasion the integral O^+ responses in all three spectrometers were comparable to or greater than the proton responses.

Figure 3 shows the latitudinal distributions of several of the various particle species measured on the satellite on this same orbit. Due to a malfunction in the stabilization system, the 1969-25B satellite was slowly tumbling and the pitch angles sampled by the various detectors are listed along the bottom of the figure. UT,L and Auroral Time are also listed. (Auroral time is a magnetic local time defined with respect to the poles of the L parameter.) During the period illustrated from 0006 to 0012 UT the satellite longitude varied from 13°E to 5°W and its altitude varied from 490 to 474 km.

In the top two panels are shown the absolute fluxes of the 9-keV O^+ ions and protons measured with the CXA-3 spectrometer. Each point represents the averaged data from the three points on the mass sweep closest to the peak of the respective ion. Channel-electron-multiplier efficiency values were taken from Burrows et al. [1968] as discussed by Shelley et al. [1972].

Several of the morphological similarities to the O^+ observations of Shelley et al. [1972] can be seen in this figure. As in the 1971 results, the peak O^+ flux was in the range L = 3 to 4 and was comparable to but somewhat greater than the proton fluxes of the same energy. The O^+ fluxes were spatially overlapping with and extended equatorward of the proton fluxes of the same energies. The peak integral energy flux of O^+ ions in the range 1-9 keV observed at 00:09:40 UT is estimated to be approximately 0.1 erg/cm^2-sec-sterad (see discussion below with respect to Figure 4). This is comparable to the peak flux of 0.4 ergs/cm^2-sec-sterad reported by Shelley et al. [1972]. These facts, plus the association of the intense O^+ fluxes with magnetic

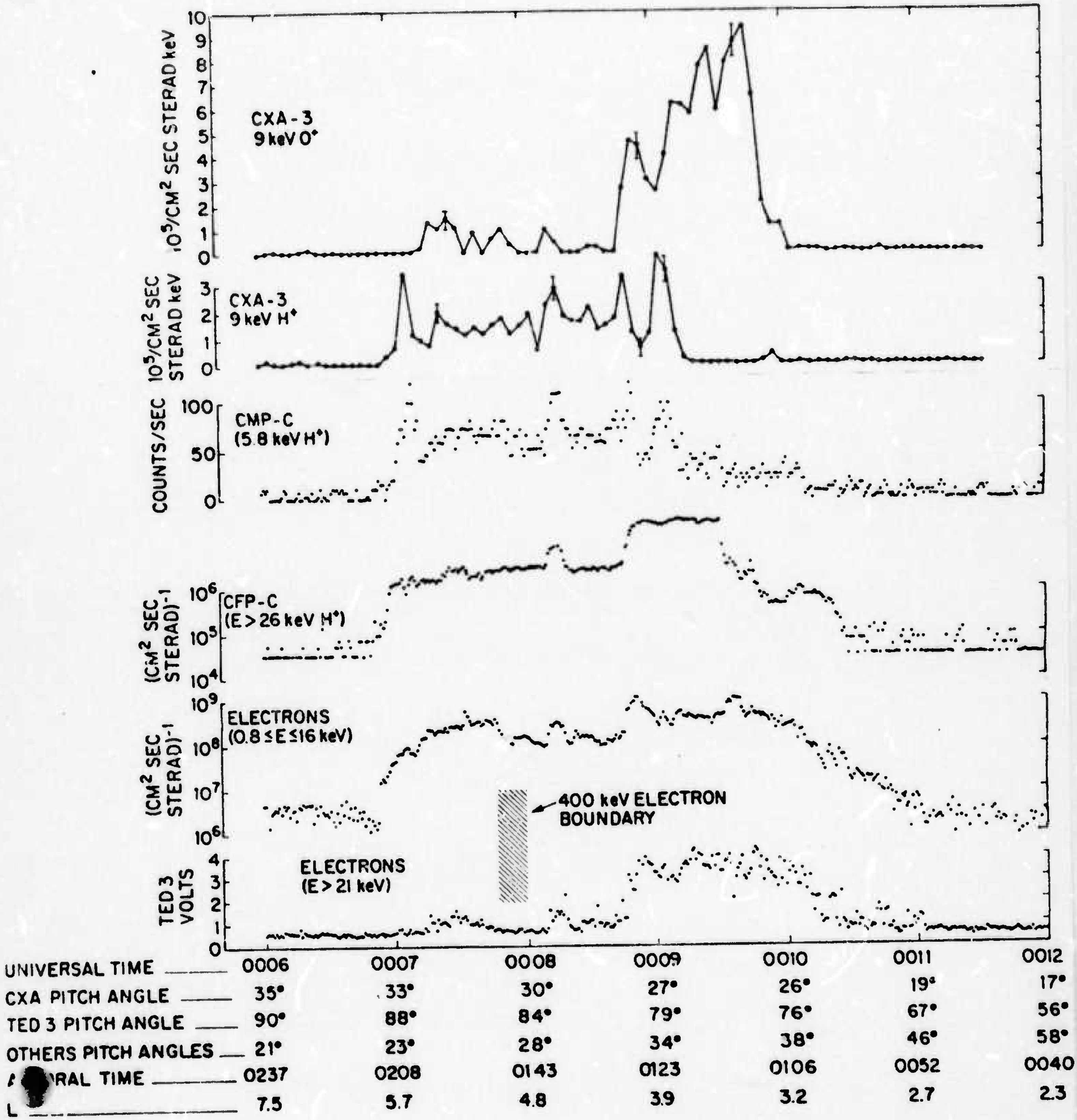

CXA-3
9 keV O+
10^5/CM² SEC STERAD keV
CXA-3
9 keV H+
10^5/CM² SEC STERAD keV
CMP-C
(5.8 keV H+)
COUNTS/SEC
CFP-C
(E > 26 keV H+)
(CM² SEC STERAD)$^{-1}$
ELECTRONS
(0.8 ≤ E ≤ 16 keV)
(CM² SEC STERAD)$^{-1}$
400 keV ELECTRON BOUNDARY
ELECTRONS
(E > 21 keV)
TED 3 VOLTS
UNIVERSAL TIME 0006 0007 0008 0009 0010 0011 0012
CXA PITCH ANGLE 35° 33° 30° 27° 26° 19° 17°
TED 3 PITCH ANGLE 90° 88° 84° 79° 76° 67° 56°
OTHERS PITCH ANGLES 21° 23° 28° 34° 38° 46° 58°
RAL TIME 0237 0208 0143 0123 0106 0052 0040
L 7.5 5.7 4.8 3.9 3.2 2.7 2.3

FIGURE 3

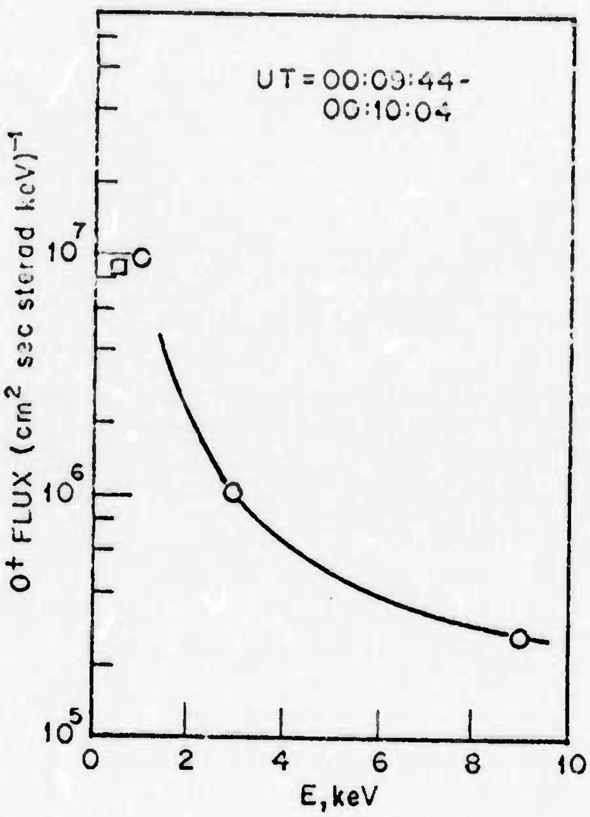

UT=00:09:44-
00:10:04
O^+ FLUX $(cm^2$ sec sterad keV$)^{-1}$
10^7
10^6
10^5
0
2
4
6
8
10
E, keV

FIGURE 4

storms in both experiments provides what we feel is convincing evidence that we are observing the same phenomena on both satellites.

In the third panel in Figure 3 is shown the response of a simple momentum analyzer called a CMP (Channeltron-Magnetic analyzer - Protons). It consists of a 35-degree bending magnet and a channel electron multiplier (channeltron). The instrument was designed to measure protons with a central energy of 5.8 keV. It has an energy bandpass ($\Delta E/E$) of about 1. It also responds to O^+ ions of the same momentum as the protons which have 1/16 the proton energy. Based on an extrapolation of the universal efficiency curve of Burrows et al. [1967], the channeltron efficiency for O^+ ions of this energy is down by about a factor of six from the efficiency for 5.8-keV protons. The folding of these efficiency values with the CMP response function yields a central energy of 0.45 keV for the instrument functioning as an O^+ detector. The CMP has a field of view of approximately $\pm 7^\circ$. It is oriented at an angle of 55° with respect to the CXA, which has a field of view of $\pm 5^\circ$. For the period of interest, the pitch angles of the particles sampled by the CMP (indicated at the bottom of Figure 2) are only a few degrees different from those sampled by the CXA. In comparing the CMP and CXA results in the following discussion we shall neglect possible angular distribution differences over this range.

In the period 00:07:00 to 00:09:10 secs UT, one sees that the CMP response generally tracks the proton fluxes in its energy range as measured by CXA-3. This is consistent with CXA-1 results (not shown) which indicate that the softer O^+ ions to which it is also sensitive are near background level during this period. In the period beyond 00:09:10 secs UT, CXA-3 shows a sharp drop of the energetic proton fluxes to background level while the O^+

ions rise to their peak intensity. The CMP shows a residual response in this period substantially higher than would be expected from the proton flux alone (compare the decrease in response from 00:09:05 to 00:09:20 UT measured in the CMP and the proton channels of CXA-3). We attribute this residual CMP response to the soft O^+ ions which are also enhanced in this period as indicated by the CXA-1 data. This is illustrated in Figure 4 where the circles show the fluxes of O^+ ions at the energies sampled by the CXA's averaged over the interval 00:09:44 to 00:10:04. This spectrum can be compared with the square symbol which shows the flux of 0.45-keV O^+ determined by the CMP under the assumption that its entire response in this period is due to O^+ ions. One sees that there is substantial agreement on the O^+ flux intensity at the low energies, as measured by these two types of instruments.

As has been indicated, we have used an extrapolated O^+ efficiency to compute the 0.45-keV O^+ flux from the CMP data and this introduces a substantial uncertainty to the measurement. The 1-keV value determined from CXA-1 also has a substantial uncertainty since, as seen in Figure 2, the Wien filter ramp extends only over the upper portion of the O^+ response function. We feel that neither of these measurements can be considered accurate to better than about a factor of 2. The fact that the CMP data agree with those of the CXA within the uncertainties as evidenced on Figure 4 provides important confirmation of the existence of the energetic heavy ions with a completely different type of spectrometer.

The remaining data on Figure 3 are included to show the relationship of the O^+ ions to other energetic particle phenomena measured on the 1969-25B satellite. The CFP-C is a threshold detector consisting of a channel-

electron-multiplier behind a 130-$\mu g/cm^2$ nickel foil which defines the energy threshold at 26 keV for protons (50% sensitivity). A broom magnet is utilized to sweep out electrons. The instrument will also respond to O^+ ions, but they must have about 16 times the energy of the protons in order to penetrate the foil [Northcliffe and Schilling, 1970] and we make the assumption that the instrument response is primarily due to protons. One sees in Figure 3 that these energetic protons are precipitating in the same general latitudinal range as the 9-keV O^+ ions and extend equatorward of the O^+ fluxes down to an L value of about 3.0.

The next plot shows the precipitating auroral electron fluxes in the range $0.8 \le E \le 16$ keV. These measurements were made with a set of four broad-band magnetic spectrometers which have been described by Paschmann et al. [1972]. The soft electrons are also seen to be precipitating down to quite low L values as a result of the intense magnetic storm.

Frank and Gurnett [1971] have shown that the high-latitude cutoff of trapped electrons with energies greater than 45 keV is an important magnetospheric boundary. It generally coincides with a reversal in the direction of the measured convection electric field and has been interpreted by these authors as the boundary between open and closed magnetic field lines.

The 1969-25B did not carry a 45-keV Geiger counter, and was at such low altitudes in the period of interest that it could not sample the stably trapped energetic outer belt electrons, but some information on the location of the O^+ fluxes relative to quasi-trapped electrons in this energy range can nevertheless be obtained. In the lower curve on Figure 3 is plotted the output of a scintillator-photomultiplier detector (TED-3) which utilized a mylar and evaporated aluminum foil to set a threshold of about

21 keV (extrapolated range) for electrons. The instrument has been described by Sharp and Johnson [1968]. The voltage output shown is approximately logarithmically related to the integral energy flux of electrons with energies well above the threshold energy. The sensitivity threshold was about 10^{-4} ergs/cm^2-sec-sterad and the dynamic range corresponding to output voltages from 1/2 to 5 volts was approximately 5 decades. The instrument had an angular acceptance of $\pm 20^{\circ}$ and reference to the pitch angle tabulations at the bottom of the figure indicates that it was sampling locally mirroring electrons in the L range above about 3.0. The TED-3 also responds to protons with energies greater than about 1/2 MeV. However, the energetic particle spectrometer of Imhof et al. [1971], which was on this same satellite, measured protons with E > 1.4 MeV and its response indicated that the proton fluxes in this energy range were sufficiently low that they do not affect the interpretation of the > 21 keV electron boundary. In examining the TED-3 data shown in Figure 3, however, one finds that this electron boundary is somewhat hard to define. There was a decrease in flux of about two orders of magnitude at 00:08:50 (L = 4.0) but it is impossible to state whether this was a temporal or spatial fluctuation. Weak fluxes were observed as far poleward at L = 5.5. The boundary is somewhere within this range.

Some supplementary information can be obtained from the energetic particle spectrometer mentioned above. This was a wide angle detector ($\pm 50^{\circ}$) which was also sampling locally mirroring electrons at the time of interest. The lowest energy electron channel on this spectrometer covered the range ($350 \leq E \leq 460$ keV) for electrons. It had a sensitivity threshold of about 0.5 electrons/cm^2-sec-sterad-keV. The spectrometer response indicated a

high-latitude cutoff at approximately the position shown by the shading in the lower part of Figure 3. The conclusion that one can draw from examining the data from both of these electron experiments is that the region of the most intense O^+ fluxes on this occasion was located equatorward of the high-latitude boundary of locally mirroring energetic electrons.

Since the source of the energetic O^+ fluxes is most likely the ionosphere, it would be of great interest to compare the fluxes with simultaneous measurements of the ambient ionospheric plasma. A retarding potential analyzer (RPA) was included in the 1969-25B payload for cold plasma measurements. It was similar in design to instruments described in earlier work [Harris et al., 1967, 1969, 1970]. The instrument had a dynamic range of four decades with a sensitivity limit corresponding to ion densities of 2.0×10^2 ions/cm^3. The RPA, however, is a direction-sensitive device, and requires a knowledge of the angle that the vehicle velocity vector makes with the normal to the plane of the entrance aperture of the instrument. Preflight dynamical analysis indicated that stabilized orientation of the spacecraft might not be achieved; therefore, four separate sensor elements were positioned co-planar with the roll-pitch plane of the vehicle. One sensor was positioned with its symmetry axis along the nominal velocity direction. Two sensors were placed with their viewing directions at $+50^\circ$ and -50° with the nominal velocity direction in the roll-pitch plane. The fourth sensor was positioned with its symmetry axis along the nominal velocity direction but with its view angle looking in the negative direction from the nominal velocity vector.

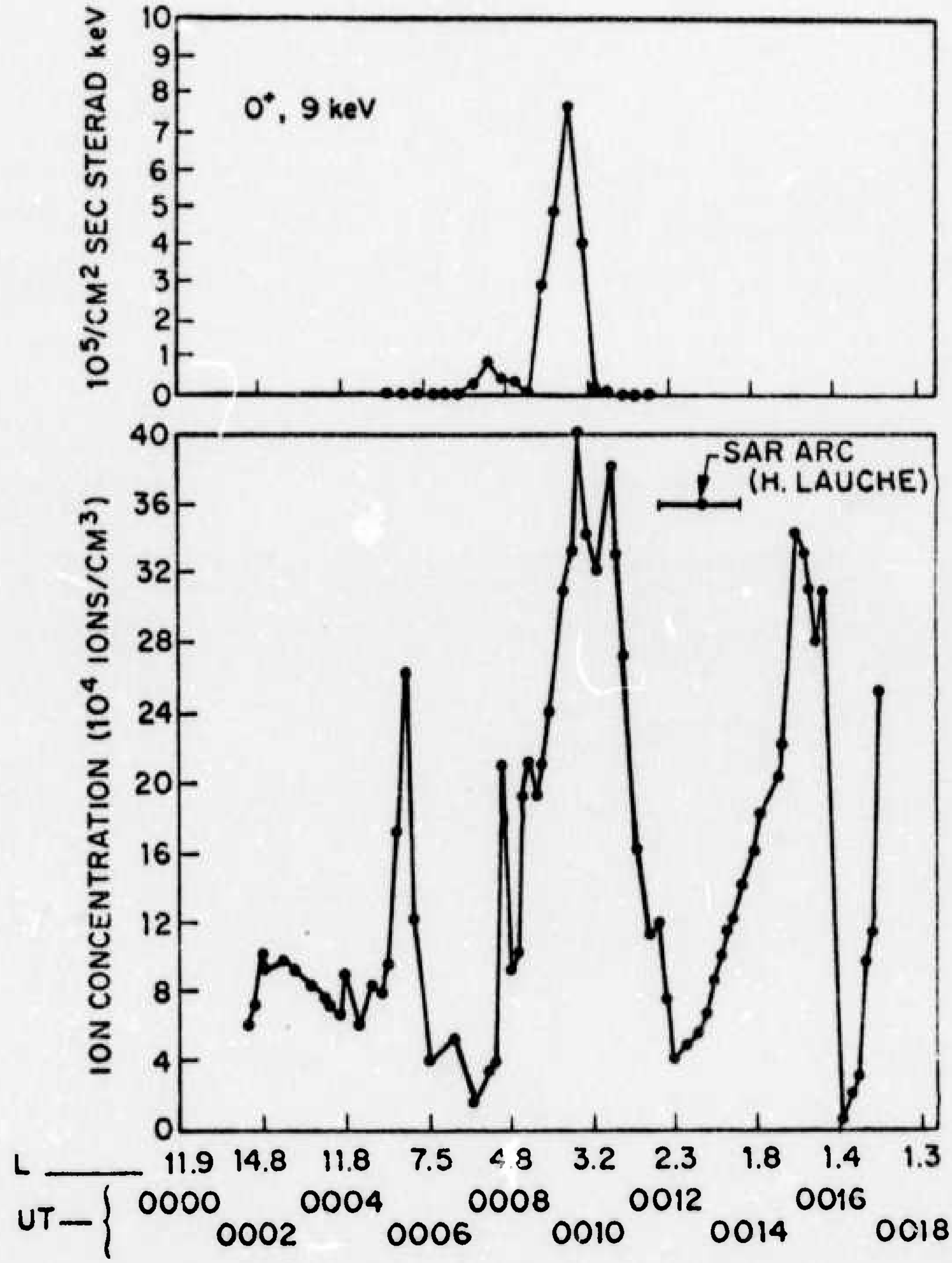
Stabilization of the spacecraft was indeed not achieved and the spacecraft executed a slow spinning-tumbling motion. In the sunlit hemisphere

the vehicle attitude could be determined directly from the solar aspect sensors carried on the spacecraft. In the nighttime region when the solar sensors were inoperative, it was possible to extrapolate the spacecraft attitude information using the outputs of the four sensors of the RPA and the magnetometer. On the orbit shown in Figure 5 the spacecraft entered the earth's shadow at 0007 UT so only a short extrapolation was required.

The data from the RPA provided an accurate measure of the ambient thermal plasma when the velocity vector of the spacecraft was in the acceptance cone of any one of the RPA sensors ($\pm 50^\circ$ with respect to the symmetry axis). For the period of time under discussion in this paper the vehicle orientation was most favorable for ion density measurements, with the velocity vector near the pitch-roll plane and sweeping through the three forward-looking sensors. The results of the ambient thermal ion density measurements are shown in Figure 5.

Twenty-second averages of the 9-keV O^+ measurements from Figure 3 are also plotted on Figure 5 for comparison with the thermal ion density. The region of intense O^+ flux is seen to correspond to the region of a steep ionospheric density gradient at the satellite altitude. This is suggestive of the possibility of an acceleration mechanism related to the gradient, operating in the altitude range below about 1000 km where the dominant ambient ion is O^+ [Taylor, 1973].

SAR-arcs are commonly observed during magnetic storms when the energetic O^+ ions have been found to be most intense. They have been shown to be located near the plasmapause [Carpenter, 1971; Hoch and Smith, 1971; Chappell et al., 1971; LaValle and Elliott, 1972; Nagy et al., 1972] and can therefore be utilized to locate the energetic O^+ ions with respect to this important



10⁵/CM² SEC STERAD keV
O⁺, 9 keV
ION CONCENTRATION (10⁴ IONS/CM³)
SAR ARC
(H. LAUCHE)
L
11.9 14.8 11.8 7.5 4.8 3.2 2.3 1.8 1.4 1.3
UT
0000 0002 0004 0006 0008 0010 0012 0014 0016 0018

FIGURE 5

magnetospheric boundary. On the night of March 23/24, 1969, Lauche [1971] has reported the observation of a SAR-arc from the Granada Observatory in the same longitude range and at the same time as the observations shown in Figure 3. The location of the SAR-arc with respect to L during the period 00:00 to 00:15 is shown in Figure 5 (Lauche, private communication). Note that the SAR-arc position, centered about $L = 2.1$, is associated with the observed depression in ambient ionospheric density. This is a commonly observed feature [Norton and Findlay, 1969; Nagy et al., 1972]. Hoch [1973] has concluded that the midpoint of the SAR-arc marks the equatorward edge of the plasmapause density gradient. This would imply that in this case the low-latitude limit of the O^+ fluxes was located about one L unit poleward of this edge of the plasmapause.

Both the data presented in this paper for the March 24, 1969 storm and the data for the December 17, 1971 storm presented by Shelley et al. [1972] show that the directional intensities of the O^+ fluxes were generally comparable to the proton fluxes in the energy range of the measurements. If the equatorial pitch-angle distributions and spectrums are the same, then the total magnetospheric populations of the two species are also comparable at these times. This has important geophysical implications. For example, since the energy density of the O^+ fluxes is four times greater than for proton fluxes of the same energies, the O^+ may dominate the ring current at these times and the total D_{ST} inferred from measurements of ring current positive ions with electrostatic analyzers under the assumption that they are protons may be substantially low. On the other hand, since the O^+ ions are of ionospheric origin, in the absence of strong pitch-angle scattering, they may exist in a narrow cone at the equator and be of much less importance to the stormtime geomagnetic field depression.

Since the O^+ observations have been made at a single angle on an oriented and a slowly-tumbling satellite, no pitch-angle distribution measurements are currently available to investigate this important question. Some preliminary guidance can be obtained at this time, however, by a consideration of the published results from the ISIS-1 satellite during this same March 24, 1969 storm. Winningham, cited by Kleckner and Hoch [1973] and Hoch et al. [1971] has reported that ISIS-1 crossed the same region of invariant latitude at a local time of 1900 hours at about the same universal time as the measurements reported here. The ISIS-1 satellite was spinning so it provided pitch-angle distribution information. Also, it was at about 3000 km altitude at the time of interest, so the data cover a wider range of equatorial pitch angles than would data from a lower-altitude satellite. The soft particle spectrometer experiment of Heikkila et al. [1970] provides data in the same energy range (up to 10 keV) as the measurements reported here. It is an electrostatic analyzer and so does not identify the mass of the measured particles. Winningham (op cit.) reported isotropic "protons" of about 0.1 erg/cm^2-sec-sterad at L values between 3.0 and 5.2 extending poleward from the vicinity of the plasmapause. As seen in Figures 3 and 5, we observe positive ion fluxes (H^+ and O^+) of comparable intensities between L = 3.2 and 6.0 extending poleward from the vicinity of the plasmapause (on the basis of the SAR-arc observations). The lowest latitude fluxes in our observations are essentially pure O^+ ions in the L range 3.3 - 3.7. If we assume that this structure persists over the five-hour local time differential between the two observations, then we would infer that the angular distribution of the O^+ ions was isotropic. Preliminary analysis of the data from a number of events from both the 1971-089A satellite [Johnson

et al., 1972] and the 1969-25B satellite [Sharp et al., 1973] indicates that the O^+ ions are observed over a wide local time range and usually extend equatorward of the protons of the same energies. Thus, there is some jusitifcation for the above assumption and some significant evidence for the isotropy of the O^+ fluxes from this intercomparison.

OTHER EVENTS

Hoch and coworkers have published the locations of a number of SAR-arcs during the period of the 1969-25B experiment [Hoch and Smith, 1971; Kleckner and Hoch, 1973]. We have searched our data for cases where we observe O^+ fluxes during the same time periods in order to obtain additional information on the location of the O^+ fluxes with respect to the plasmapause. These cases are summarized in Table I. Since the O^+ fluxes were always located poleward of the corresponding SAR-arc, we have listed the lowest L value at which the O^+ fluxes were observed above background on a given satellite pass (L_{MIN}). Since the duty cycle for acquiring the satellite data was relatively low (only about 10 orbits of data, of 90 minutes duration each, were acquired per week), we found that in general no simultaneous data, or data at the relevant longitude, for comparison with the SAR-arcs were available. An example of the uncertainties introduced by such a lack of exact coordination can be seen in the differences in position of the SAR-arc over Granada at 0000 UT on March 24 (Figure 5) and over Richland three hours later (Table I). SAR-arcs are more commonly stable in position over long periods of time, however, and often extend over a

O^+ OBSERVATIONS					SAR-ARCS						
DATE	UT	L_{MIN}	AT (HRS)	HEM	DATE	UT OBSERVED	AVERAGE L VALUE	** REF.	Δ LON (DEG)	Δ UT (HRS)	Δ L
March 24, 1969	1807	5.7*	21	S	March 24, 1969	0300-1130	2.7-2.9	KH	179	6	2.9*
					March 25, 1969	0859-1144	3.0-3.1	HS	179	15	
May 15, 1969	1340	4.3	24	N	May 15, 1969	0551-1021	2.5-3.0	KH, HS	68	3	1.5
May 15, 1969	2311	4.2	2	N					147	13	1.4
Sept. 29, 1969	1850	3.0	2	N	Sept. 30, 1969	0234-0343	2.6-2.9	KH, H	125	8	0.2
Sept. 29, 1969	1919	4.4	24	S					158	7	1.6
Sept. 30, 1969	1214	3.9	1	N					150	9	1.1
										Average:	1.2

TABLE I

* Data gap, L = 3.4-5.2, deleted from average

** KH = Kleckner and Hoch [1973]
HS = Hoch and Smith [1971]
H = R. J. Hoch (private communication)

wide range of longitude with only moderate variation in L [Roach and Roach, 1963], so it is felt that some information on the relative location of the O^+ fluxes and the plasmapause can be derived, at least on a statistical basis, even when the coordinations were not exact. A measure of the relative closeness of the coordination in each case is provided by the Δ UT, Δ LON columns in Table I which show the differences in these quantities between the satellite and ground-based observations. The last column shows the difference between the average L value of the SAR-arc and L_{MIN}. One sees that on the average the low latitude limit of the O^+ fluxes is located about one L unit poleward of the SAR-arcs and hence is inferred to be displaced about that distance from the high-density (equatorward) edge of the plasmapause [Hoch, 1973]. This is in agreement with the result from the pass near 0 UT on March 24 (Figure 5) where a more exact set of coordination conditions was obtained.

SUMMARY AND CONCLUSIONS

The location of the energetic O^+ fluxes observed during a satellite pass on March 24, 1969 has been compared with simultaneous on-board measurements of other energetic particles and the ambient cold plasma. The most intense O^+ fluxes were located equatorward of the high-latitude boundary of locally mirroring energetic electrons and overlapping but extending equatorward of proton fluxes of the same energy. They also were spatially overlapping with precipitating fluxes of auroral electrons and energetic outer belt protons. They were located at the position of a steep density

gradient in the ambient plasma in the altitude range where O^+ is the dominant ionospheric constituent. This may be a clue to their origin.

The identification of the particles as energetic heavy ions by the mass spectrometer experiment has been confirmed by measurements with an independent instrument.

A comparison with measurements from the ISIS-1 satellite has provided some evidence for an isotropic angular distribution for the O^+ ions at 3000 km altitude on this occasion.

Comparisons of the locations of the O^+ fluxes on seven occasions with SAR-arc observations acquired during the same magnetic storms has indicated that on the average the low-latitude limit of the O^+ observations was about one L unit poleward of the SAR-arc. It is inferred, therefore, that they are located poleward of the plasmapause by about this distance.

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FIGURE CAPTIONS

FIGURE 1 A schematic drawing of one of the three channels of the energetic ion mass spectrometer (CXA).

FIGURE 2 Mass-per-unit-charge spectrums from one of the 1971-089A spectrometers (top left) and from the three 1969-25B spectrometers. The 1969-25B data were acquired on March 24, 1969. The expected positions of the various mass peaks are indicated by arrows.

FIGURE 3 Data from several instruments on the 1969-25B satellite during a traversal of the northern hemisphere on March 24, 1969.

FIGURE 4 Energy spectrum of O^+ ions during the indicated period on March 24, 1969. The circles represent data from the CXA spectrometers and the square represents data from the CMP spectrometer.

FIGURE 5 Data from CXA-3 (top panel) and the retarding potential analyzer (bottom panel) on March 24, 1969 during the same satellite traversal for which additional data are illustrated in Figure 3. The location of a SAR-arc measured simultaneously from the observatory in Granada, Spain is also indicated (H. Lauche, private communication).